3 Equations and Models for Calculating Dose to Biota and Deriving BCGs

Based on the potential pathways of exposure, BCGs were derived for surface water, sediment, and soil. Calculated using conservative assumptions, the BCGs are intended to preclude the relevant biota from being exposed to radiation levels in excess of established or recommended biota dose limits. Determination of compliance with the dose limits requires that all organism-relevant environmental media be evaluated at the same time. This is done by using the “sum of fractions” approach commonly used in evaluating radionuclide discharges to the environment.

3.1 An Important Note on Estimating Internal Tissue Concentrations for Use in Dose Equations: The Lumped Parameter

For most radionuclides, the single most important predictor of biota dose is the method used to estimate internal tissue concentrations. For the general screening phase of the graded approach, lumped parameters were used to provide estimates of organism tissue concentration, and ultimately derive the BCG corresponding to each radionuclide, media, and organism type. The technical literature contains reference to empirically-based parameters which measure concentrations of contaminants in an organism relative to the surrounding media. These ratios are called “concentration ratios,” “concentration factors,” or “wet-weight concentration ratios” (B_{iv}s). These lumped parameter (e.g., B_{iv}) values are available for many radionuclides for plant:soil and for aquatic species:water. In a few instances they are also available for animal:soil or sediment. The advantage of using one of these factors is that it allows the prediction of tissue concentration based on simple measurements of contamination in environmental media such as water, sediment and soil.

The selection of a value for this lumped parameter becomes problematic, however, when considering the range of organism types meant to be covered by the graded approach. For example, there is very limited data available for riparian and terrestrial animals (i.e., very limited animal:water, animal:soil, and animal:sediment concentration ratios). As the graded approach methodology evolved it became apparent that these data gaps (e.g., for selecting appropriate lumped parameters) needed to be addressed. Two alternative approaches for deriving and selecting lumped parameters were evaluated:

- **Calculating the lumped parameter values by multiplying related concentration ratios (product approach).** For example, the product of plant:soil and animal:plant concentration ratios yields an animal:soil ratio which may be used as the lumped parameter for a terrestrial animal. This approach must be used with caution, as the data used in the process are most likely from different sources. This approach is also hampered by the general lack of environmental data.

- **Calculating the lumped parameter values by using uncertainty analysis on the kinetic/allometric method.** The kinetic/allometric method, as used in the analysis phase of the graded approach, is based on mathematically modeling the exposure of an organism using simplistic, first-order kinetic reactions. There are several allometric equations which relate body size to many of the parameters contributing to internal dose (e.g., to include ingestion rates, life span, and inhalation rate). Uncertainty analysis (e.g., using Monte Carlo techniques) on each of the allometric equations, and on their corresponding parameters varied over their known ranges of values, can provide an upper bound estimate (i.e., at the 95^{th} percentile) of lumped parameter values for those organism types (riparian and terrestrial animals) for which there is limited empirical data.

These alternative approaches, and the rationale for their use, are discussed further in Section 3.4. Figure 3.1 shows the logic flow for the derivation and selection of default lumped parameter values employed in the general screening phase for each of the four organism types addressed in the graded approach.

Figure 3.1 Process for Selecting Default B_{iv}/Lumped Parameter Values for Use in the General Screening Phase of the Graded Approach

	Aquatic Animal	Riparian Animal	Terrestrial Plant	Terrestrial Animal
(1) B_{iv}s/ lumped parameters compiled for each organism type (literature searches; models; empirical data)	Very good empirical data	Fair to limited	Very good empirical data	Fair to limited
(2) B_{iv}s/ lumped parameter data sets reviewed for quality, quantity, and range of values	Very good	Limited: RA: water RA: sediment Some: RA(fs) : sediment RA: RA(fs)	Very good	Limited: TA: water TA: soil Some: TA: soil TA: TP
(3) For Fair/ Limited Data:				
(3a) B_{iv}/ lumped parameters estimated using product approach (e.g. multiplying concentration ratios, CRs)	-	(RA(fs) : sediment) • (RA • RA(fs)) yields (RA: sediment)	-	(TP: soil) • (TA: TP) yields (TA: soil)
(3b) Lumped parameters estimated by using uncertainty analysis on the kinetic/allometric method (95th percentile of resulting distributions)	-	Uncertainty analysis on each allometric equation and their corresponding parameters varied over their known ranges of values.	-	Uncertainty analysis on each allometric equation and their corresponding parameters varied over their known ranges of values.
(3c) B_{iv}/ lumped parameter value comparison: product approach; uncertainty analysis (K/A method); available empirical data	-	B_{iv}/ lumped parameter comparison: product approach; uncertainty analysis (K/A method); empirical data	-	B_{iv}/ lumped parameter comparison: product approach; uncertainty analysis (K/A method); empirical data
(4) B_{iv}/ lumped parameter values selected as default values for general screening.	empirical values used	Preference for empirical values where available and of sufficient quality; otherwise uncertainty analysis (K/A method) values	empirical values used	Preference for empirical values where available and of sufficient quality; otherwise uncertainty analysis (K/A method) values

KEY		
AA	=	Aquatic Animal
RA	=	Riparian Animal
TP	=	Terrestrial Plant
TA	=	Terrestrial Animal
RA(fs)	=	Food source to a Riparian Animal
Uncertainty Analysis (K/A Method)	=	Uncertainty analysis on kinetic/allometric method

3.2 Equations and Models for Aquatic Systems

3.2.1 Aquatic Animals

Sediment BCGs for Aquatic Animals. The conceptual model for aquatic animals places the organism at the sediment-water interface. In this screening model, sediment presents an external dose hazard to the aquatic animal, with the BCG therefore based on a semi-infinite exposure model. Uptake of contaminants from the sediment to the organism is implicitly addressed via the empirical organism to water lumped parameter discussed in following sections. The method used to derive the aquatic animal BCGs for exposure to a single nuclide in contaminated sediment is:

$$BCG(sediment)_{i,\text{aquatic animal}} = \frac{365.25 \cdot DL_{aa}}{CF_{aa} \cdot DCF_{ext,sediment,i}}$$

Equation 1

where $BCG(\textit{sediment})_{i,\text{aquatic animal}}$ (Bq kg^{-1}) is the concentration of nuclide *i* in sediment which, based on the screening level assumptions, numerically equates to a dose rate of DL_{aa} (0.01 Gy d^{-1}) to the aquatic animal;

365.25 (days per year) is a conversion factor;

DL_{aa} (0.01 Gy d^{-1}) is the dose limit for aquatic animals. This limit can be adjusted by the user if so directed by an appropriate agency;

$DCF_{ext,sediment,i}$ (Gy y^{-1} per Bq kg^{-1}) is the external dose conversion factor used to estimate the dose rate to the tissues of the aquatic animal from nuclide *i* in the sediment; and

CF_{aa} (dimensionless) is the correction factor for area or organism residence time. This correction factor is set at a default of 1.

It should be noted that Equation 1 can also be used to evaluate compliance for aquatic plants. Both the dose factor and dose limit are the same.

Water BCGs for Aquatic Animals. The conceptual model for aquatic animals places the organism at the sediment-water interface. In this screening model, water presents both an internal and external dose hazard to the aquatic animal. Lumped parameters (e.g., bioaccumulation factors) are used to estimate the extent of internal contamination (and by extension, the dose), and external exposure is assessed with a semi-infinite source term. The method used to derive the screening-level aquatic animal BCGs for exposure to a single nuclide in contaminated water is:

$$BCG(water)_{i,\text{aquatic animal}} = \frac{365.25 \times DL_{aa}}{CF_{aa} \times \left[\left(0.001 \times B_{iv,aa} \times DCF_{internal,i} \right) + \left(DCF_{external,water,i} \right) \right]}$$

Equation 2

where $BCG(\textit{water})_{i,\text{aquatic animal}}$ (Bq m^{-3}) is the concentration of nuclide *i* in water which, based on the screening level assumptions, numerically equates to a dose rate of DL_{aa} (0.01 Gy d^{-1}) to the aquatic animal;

DL_{aa} (0.01 Gy d^{-1}) is the dose limit for aquatic animals. This limit can be adjusted by the user if so directed by an appropriate agency;

0.001 is the conversion factor for L to m^3;

$B_{iv,aa,i}$ (Lkg^{-1}) is the fresh mass aquatic animal to water concentration factor for nuclide *i*;

$DCF_{internal,i}$ (Gy y^{-1} per Bq kg^{-1}) is the dose conversion factor used to estimate the dose rate to the tissues from nuclide *i* in tissues;

$DCF_{external,\ water,i}$ (Gy y^{-1} per Bq m^{-3}) is the dose conversion factor used to estimate the dose rate to the aquatic animal from submersion in contaminated water; and

all other terms have been defined.

It should be noted that Equation 2 can also be used to evaluate compliance for aquatic plants. Both the dose factor and the dose limit are the same. In lieu of an aquatic animal B_{iv}, simply substitute an aquatic plant concentration factor.

3.2.2 Riparian Animals

Sediment BCGs for Riparian Animals. The conceptual model for riparian animals also places the organism at the sediment-water interface (as does the aquatic animal model). However, in this screening model, sediment presents both an internal and external dose hazard to the riparian animal. Lumped parameters are used to estimate the extent of internal contamination (and by extension, the dose), and external exposure is assessed with a semi-infinite source term. The method used to derive the riparian animal BCGs for exposure to a single nuclide in contaminated sediment is:

$$BCG(sediment)_{i,\text{riparian animal}} = \frac{365.25 \times DL_{ra}}{CF_{ra} \times [(LP_{ra,sed,i} \times DCF_{internal,i}) + (DCF_{ext,sediment,i})]}$$

Equation 3

where BCG(*sediment*)$_{i,\text{riparian animal}}$ (Bq kg^{-1}) is the concentration of nuclide *i* in sediment, based on the screening level assumptions, numerically equates to a dose rate of DL_{ra} (0.001 Gy d^{-1}) to the riparian animal;

DL_{aa} (0.001 Gy d^{-1}) is the recommended dose limit for riparian animals. This limit can be adjusted by the user if so directed by an appropriate agency;

$LP_{ra,sed,i}$ (dimensionless) is the fresh mass riparian animal to sediment concentration factor of nuclide *i*;

CF_{ra} (dimensionless) is the correction factor for area or organism residence time for the riparian organism. This correction factor is set at a default of 1; and

all other terms have been defined.

Water BCGs for Riparian Animals. As noted previously, the conceptual model for riparian animals has the animal situated at the sediment-water interface. In assessing potential contributors to dose, water presents both an internal and external dose hazard. As before, lumped parameters are used to estimate the extent of internal contamination. External exposure is assessed with a semi-infinite source term. The method used to derive the screening-level riparian animal BCGs for exposure to a single nuclide in contaminated water is as follows:

$$BCG(water)_{i,\text{riparian animal}} = \frac{365.25 \times DL_{ra}}{CF_{ra} \times [(0.001 \times LP_{ra,water,i} \times DCF_{internal,i}) + (DCF_{ext,water,i})]}$$

Equation 4

where BCG(*water*)$_{i,\text{ riparian animal}}$ (Bq m^{-3}) is the concentration of nuclide *i* in water, which based on the screening level assumptions, numerically equates to a dose rate of DL_{aa} (0.001 Gy d^{-1}) to the riparian animal;

$LP_{ra,water,\ i}$ (L/kg) is the fresh mass riparian animal to water concentration factor of nuclide *i*; and

all other terms have been defined.

3.2.3 Important Considerations When Implementing Equations and Models in an Aquatic System Evaluation

For the aquatic environment, compliance with the dose limit is determined by comparison of the projected dose from both water and sediment. This is achieved by using a sum of fractions approach. The measured concentrations of radionuclides for the water and sediment pathways are each ratioed to their respective BCGs and the resultant values summed. If the total is less than one, then compliance (for that nuclide) is achieved. For multiple nuclides the process is repeated, with the sum of all fractions (the grand total) required to be less than one for compliance.

Co-located water and sediment samples. The preferred method of determining compliance is to use co-located water and sediment data. If such data are available, then compliance is determined in the manner described in the preceding paragraph.

Water and sediment samples not co-located. In situations where co-located water and sediment data are not available, the user estimates the missing data through use of the radionuclide-specific “most probable” distribution coefficient. If water data are present, but sediment data are unavailable, the missing sediment data are estimated through use of the following calculation:

$$C_{sediment} = 0.001 \times C_{water} \times K_{d,most\ probable}$$

Equation 5

where $C_{sediment}$ (Bq kg^{-1}) is the concentration of nuclide *i* in sediment;

0.001 (m^{3} L^{-1}) is the conversion factor for L to m^{3};

C_{water} (Bq m^{-3}) is the concentration of nuclide *i* in water; and

$K_{d,most\ probable}$ (expressed as L kg^{-1} but also equates to mL g^{-1}) is the distribution coefficient used to relate the water concentration to the sediment concentration. In doing this calculation, median values of distribution coefficients were selected, rather than extreme values. For many nuclides, distribution coefficients range over several orders of magnitude. Selection of extreme values would result in unrealistic projections of water (or sediment) concentrations of radionuclides.

Conversely, if water data are unavailable, the RAD-BCG Calculator estimates the missing water data through use of the following calculation:

$$C_{water} = \frac{C_{sediment}}{0.001 \times K_{d,most\ probable}}$$

Equation 6

where all terms have been previously defined.

If the user has water data from one location, and sediment data from another (for the same radionuclide), they should use both approaches outlined above, and select the method which results in the highest (e.g., most conservative) partial fraction.

3.3 Equations and Models for Terrestrial Systems

3.3.1 Terrestrial Plants

Soil BCGs for Terrestrial Plants. In this screening model, soil provides both an internal and external dose hazard to plants. The conceptual model for terrestrial plants is based on the entire plant being surrounded by soil. While many plants may have a substantial portion of their mass above ground, the BCG thus derived, will be conservative. Lumped parameters (e.g., bioaccumulation factors) are used to estimate the extent of internal contamination (and by extension, the dose), and external exposure is assessed using an infinite source term. The lumped parameters used in the model account for aerial deposition onto plant surfaces with subsequent uptake. The method used to derive the BCGs for terrestrial plant exposure to a

$$BCG(soil)_{i,terrestrial\ plant} = \frac{365.25 \times DL_{tp}}{CF_{tp} \times [(B_{iv,tp,i} \times DC_{internal,i}) + (DCF_{ext,soil,i})]}$$

single nuclide in contaminated soil is:

Equation 7

where $BCG(\textit{soil})_{i,terrestrial\ plant}$ (Bq kg^{-1}) is the concentration of nuclide *i* in soil which, based on the screening level assumptions, numerically equates to a dose rate of DL_{tp} (0.01 Gy d^{-1}) to the terrestrial plant;

DL_{tp} (0.01 Gy d^{-1}) is the recommended dose limit for terrestrial plants. This limit can be adjusted by the user if so directed by an appropriate agency;

$B_{iv,tp,i}$ (dimensionless) is the fresh mass terrestrial plant to soil concentration factor;

CF_{tp} (dimensionless) is the correction factor for area or time. This correction factor is set at a default of 1;

$DCF_{ext,\ soil,i}$ (Gy y^{-1} per Bq kg^{-1}) is the dose conversion factor used to estimate the dose rate to the plant tissues from nuclide *i* in surrounding soils; and

all other terms are as previously defined.

It should be noted that the derivation of the water BCG for terrestrial plants only considers external exposure of plants from submersion in water. Although this may seem to ignore uptake of contaminants from pore water into the plant, there is very limited data available to support this type of calculation. The best estimator of internal deposition is the plant-to-soil uptake factor, utilized in Equation 7. If only water data is available, and no soil data (for example, measurements in irrigation water), you can use the relationship outlined in Equation 5 to predict the soil concentration and substitute this value into Equation 7.

Water BCGs for Terrestrial Plants. The conceptual model for terrestrial plants is based on the entire plant being surrounded by soil. However, the potential for exposure to contaminated water – from soil pore water or from irrigation exists. As a compromise to the methodology, external exposure from water was added. In this screening model, the BCG for water is based on a semi-infinite exposure model. The method used to derive the BCGs for terrestrial plant exposure to a single nuclide in contaminated water is:

$$BCG(water)_{i,terrestrial\ plant} = \frac{365.25 \times DL_{tp}}{CF_{tp} \times DCF_{ext,water,i}}$$

Equation 8

where BCG(*water*)$_{i,terrestrial\ plant}$ (Bq m^{-3}) is the concentration of nuclide *i* in soil which, based on the screening level assumptions, numerically equates to a dose rate of DL_{tp} (0.01 Gy d^{-1}) to the terrestrial plant; and

all other terms are as previously defined.

3.3.2 Terrestrial Animals

Soil BCGs for Terrestrial Animals. The screening conceptual model for terrestrial animals has the animal surrounded by soil. In assessing potential contributors to dose, soil presents both an internal and external dose pathway. As before, lumped parameters are used to estimate the extent of internal contamination (e.g., as might occur from ingestion or inhalation). External exposure is assessed with an infinite source term. The method used to derive the terrestrial animal BCGs for exposure to a single nuclide in contaminated soil is:

$$BCG(soil)_{i,\text{terrestrial animal}} = \frac{365.25 \times DL_{ta}}{CF_{ta} \times [(LP_{ta,soil,i} \times DCF_{internal,i}) + (DCF_{ext,soil,i})]}$$

Equation 9

where BCG(*soil*)$_{i,\text{ terrestrial animal}}$ (Bq kg^{-1}) is the concentration of nuclide *i* in soil which, based on the screening level assumptions, numerically equates to a dose rate of DL_{ta} (0.001 Gy d^{-1}) to the terrestrial animal;

DL_{ta} (0.001 Gy d^{-1}) is the recommended dose limit for terrestrial animals. This limit can be adjusted by the user if so directed by an appropriate agency;

$LP_{ta,soil,i}$ (dimensionless) is the fresh mass terrestrial animal to soil concentration factor of nuclide *i*;

CF_{ta} (dimensionless) is the correction factor for area or organism residence time for the terrestrial organism. This correction factor is set at 1 for the general screening phase of the calculations; and

all other terms have been defined.

Water BCGs for Terrestrial Animals. The conceptual model for terrestrial animals is based on the entire animal being surrounded by soil. However, the potential for exposure to contaminated water from soil pore water or by drinking from contaminated ponds or rivers exists. Water presents both an internal and external dose hazard. As before, lumped parameters are used to estimate the extent of internal contamination (e.g., as might occur from ingestion). A semi-infinite exposure model is used for the external exposure. The method used to derive the terrestrial animal BCGs for exposure to a single nuclide in contaminated water is:

$$BCG(water)_{i,\text{terrestrial animal}} = \frac{365.25 \times DL_{ta}}{C_{ta} \times [(0.001 \times LP_{ta,water,i} \times DCF_{internal,i}) + (DCF_{ext,water,i})]}$$

Equation 10

where BCG(*water*)$_{i,\text{ terrestrial animal}}$ (Bq m^{-3}) is the concentration of nuclide *i* in water which, based on the screening level assumptions, numerically equates to a dose rate of DL_{ta} (0.001 Gy d^{-1}) to the terrestrial animal;

$LP_{ta,\ water,\ i}$ (L/kg) is the fresh mass terrestrial animal to water concentration factor of nuclide *i*; and

all other factors have been defined.

How are these Dose Equations and their Parameters Used in Implementing the Graded Approach?

General Screening. The initial value of the "lumped parameter" (B_{iv}) used in the general screening phase is specifically chosen to produce conservative default BCGs. This quickly removes from further consideration contamination levels that would not cause biota to receive doses above acceptable limits. However, some sites may fail the general screen. This does not mean that they are causing biota to receive doses above the acceptable limit, but suggests that further analysis is warranted for specific radionuclides and media. It is recognized that actual B_{iv} values range over several orders of magnitude, depending upon biotic and abiotic features of the environment.

Site-Specific Screening. The next step is to examine the lumped parameter, and using data either directly from the site, or from the technical literature, select a value which is more representative for the specific-site conditions. In doing so, the screening calculation is repeated and a new site-specific BCG is provided. The process for each organism-type is as follows:

- **Aquatic Animals.** The user is allowed to modify the $B_{iv,aa,i}$ (the wet weight bioaccumulation factor) to a more site-representative value. All other aspects of the calculations remain the same.

- **Riparian Animals.** The user is allowed to modify the lumped parameter ($LP_{ra,water,I}$ and $LP_{ra,sed,I}$, the wet weight bioaccumulation factor for animal to water or animal to sediment) to a more site-representative value. All other aspects of the calculations remain the same.

- **Terrestrial Plants.** The user is allowed to modify the $B_{iv,tp,i}$ (the wet weight bioaccumulation factor) to a more site-representative value. All other aspects of the calculations remain the same.

- **Terrestrial Animals.** The user is allowed to modify the lumped parameter ($LP_{ta,water,I}$ and $LP_{ta,soil,I}$, the wet weight bioaccumulation factor for terrestrial animal to water or terrestrial animal to soil) to a more site-representative value. All other aspects of the calculations remain the same.

3.4 Alternatives to Lumped Parameters for Riparian and Terrestrial Animals: The Kinetic/Allometric Method

As discussed in Section 3.1, for most radionuclides, the single-most important predictor of biota dose is the method used to estimate internal tissue concentrations. The technical literature contains reference to these empirically based parameters that measure concentrations of contaminants in an organism relative to the surrounding media. These ratios are called "concentration ratios," "concentration factors," or "wet-weight concentration ratios" (B_{iv}s). These lumped parameters (e.g., B_{iv} values) are available for many nuclides for plant:soil and for aquatic species:water. In a few instances they are also available for animals:soil or animals:sediment. The advantage of using one of these factors is that it allows the prediction of tissue concentration based on simple measurements of contamination in environmental media such as soil, water, or sediment. The use of lumped parameters is an integral feature of the screening approach. However, as the methodology evolved it became apparent that there were gaps in the data that needed to be addressed, particularly for riparian and terrestrial animal lumped parameters. An alternative approach, called the kinetic/allometric method, was developed. This method had two objectives: first, to fill in data gaps in the literature on lumped parameters; and second, to provide users with an alternative, more sophisticated method for evaluating dose to specific riparian and terrestrial animal receptors.

The kinetic/allometric method is applied in the site-specific analysis component of the graded approach. In site-specific analysis, the internal pathways of exposure are examined in greater detail. This evaluation relies upon mathematically modeling the exposure of the organism using simplistic, first-order kinetic reactions of the form:

$$q = \frac{R}{k}(1-e^{-kt})$$

Equation 11

where q is the total activity (Bq) in the organism of concern at time t;

R is the intake rate of activity (Bq d^{-1}) into the organism;

k is the effective loss rate of activity (d^{-1}) from the organism; and

t is the total length of exposure to the contaminant (d).

The activity concentration in the animal is calculated as q divided by the mass; in SI units the mass would be expressed in kg. While this calculation method is simple, it still requires information on the intake rate of the organism, the total body mass, the loss rate of the radionuclide and the exposure period.

3.4.1 A Scaling Approach to Predicting Tissue Concentrations

The key to estimating body burdens in biota is an expression for intake that can account for potential change with size of the organism. There are several allometric equations which relate body size to many parameters, including ingestion rate, life span, inhalation rate, home range and more (West et al. 1997). These equations take the form of:

$$Y = \alpha X^{\beta}$$

Equation 12

where Y and X are size-related measures and α and β are constants.

While these equations were originally derived from empirical observations, there is a growing body of evidence that these relationships have their origins in the dynamics of energy transport mechanisms. An example of one use of this type of equation is illustrated in deriving soil BCGs for terrestrial animals.

3.4.1.1 Estimating Intake (Soil Pathway)

The intake of radioactivity into a terrestrial animal is presumed to come from three routes of exposure: ingestion of contaminated foodstuffs, ingestion of contaminated soil, and inhalation of re-suspended soil.

Ingestion of food. Metabolic rate is known to scale to body mass to the ¾ power (Calder 1984, Reiss 1989, and West et al. 1997). The food intake rate can also be calculated if allowances are made for several factors (Whicker and Shultz 1982):

$$r = \frac{a}{dc} 70M^{0.75}$$

Equation 13

where r = food intake rate in g/day;

a = ratio of active or maintenance metabolic rate to the basal metabolic rate;

d = fraction of the energy ingested that is assimilated and oxidized;

c = caloric value of food in kcal /g; and

M = live body weight in kilograms.

The rate of radionuclide intake into the animal is a product of the food intake rate and the activity concentration of the foodstuff. The concentration of radionuclides in food is a product of the soil concentration (C_s, Bq/kg) and the food-to-soil uptake factor ($B_{iv,tp,i}$ dimensionless). The radionuclide intake rate via ingestion is expressed in Bq/d:

$$I_{ingestion,food,i} = C_{s,i} B_{iv,tp,i} \left[10^{-3} \frac{a}{dc} 70M^{0.75} \right]$$

Equation 14

Where $I_{ingestion,food,i}$ is the intake rate (Bq d^{-1}) of a radionuclide into the animal via consumption of contaminated food, the concentration of radionuclides in the contaminated food is calculated as a product of the soil concentration and the food-to-soil (wet-weight) uptake factor (B_{iv}), and the factor of 10^{-3} converts the ingestion rate of equation 13 from g d^{-1} to kg d^{-1}; and

all other terms have been defined.

Ingestion of soil. Studies on soil ingestion by wildlife indicate that it scales as a percentage of the mass of the daily diet (EPA 1993). The rate of radionuclide intake into the animal via soil ingestion (Bq d^{-1}) would therefore be the soil concentration times the daily mass of food ingested times the fraction of the daily diet that comes from soil ingestion (f).

$$I_{ingestion,soil,i} = C_{s,i} \; f \left[10^{-3} \frac{a}{dc} 70 M^{0.75} \right]$$

Equation 15

where f is the fraction of the mass of daily diet that comes from soil ingestion.

Inhalation of soil. The rate of intake of soil into the lungs of the animal can be calculated as the product of the inhalation rate (m^3 d^{-1}) and the air concentration (in Bq m^{-3}) of the nuclide.

The air concentration can be estimated using the mass loading approach. The activity in air is calculated as the product of X, the dust loading in air (in kg m^{-3}) and $C_{soil.}$ The lung ventilation rate also scales as a function of body mass (Pedley 1975 and West et al. 1997). Because of differences in solubility in body fluids, material taken into the body via inhalation may (or may not) be more readily absorbed than those taken in via ingestion. In his paper assessing the contribution of inhalation to dose, Zach (1985) derived a series of correction factors (PT/IT) which provided an adjustment for inhalation relative to ingestion. These factors are used to correct the inhalation rate to that of an equivalent amount of ingested soil:

$$I_{inhalation,normalized,i} = \frac{PT}{IT} \; X \; C_{s,i} \; 0.481 \; M^{0.76}$$

Equation 16

Calculating Total Intake. The total intake to the body can be calculated as the sum of inputs from inhalation given in equation 16, food ingestion in equation 14, and soil ingestion in equation 15. This is accomplished by direct substitution and rearrangement into the relationship $R = I_{inhalation} + I_{soil\ ingestion} + I_{food}$, as follows:

$$R = C_{soil}\left[(B_{iv} + f)\left(10^{-3}\frac{a}{dc}70M^{0.75}\right) + \frac{PT}{IT}X\ 0.481M^{0.76}\right]$$

Equation 17

Estimating the Fraction Assimilated into the Body. Because only a fraction of the material ingested actually enters into the blood, the total intake rate must be modified by a factor, f_1, to account for this difference:

$$R^* = f_1 R = f_1 C_{soil}\left[(B_{iv} + f)\left(10^{-3}\frac{a}{dc}70M^{0.75}\right) + \frac{PT}{IT}X\ 0.481M^{0.76}\right]$$

Equation 18

where R* is the species-independent estimate of radionuclide uptake to blood (Bq d^{-1}) from exposure to contaminated soil, and f_i is the fraction of intake assimilated to the body.

3.4.1.2 Estimating the Total Loss Rate from the Organism

The loss of radioactive material from the organism is due to radiological decay as well as biological elimination. There is substantial evidence that biological half-time of material in the body is related to metabolism, and therefore should be a function of body mass with the following relationship:

Equation 19

$$T_{1/2,biological,i} = \alpha W^{\beta}$$

where α and β are scaling constants related to the biological elimination of a particular element and W is the body mass (in g). In their book, Whicker and Schultz (1982) identified empirical relationships for five elements including Sr, Cs, I, Co, and ^3H. Three of these elements exhibited scaling to the ¼ power (Cs, Sr, Co). Iodine scaled at $W^{0.13}$ and ^3H scaled at $W^{0.55}$. The biological decay time is then used to calculate the biological decay constant (e.g, k in Equation 11). The effective decay constant, k_{eff} is calculated as the sum of the radiological and biological decay constants.

Scaling constants for other radionuclides were estimated from data provided in the literature on the biological elimination rates for various species of animals.

3.4.1.3 Calculating the Fractional Buildup to Equilibrium Tissue Concentrations

The activity in an organism continuously exposed to a constant source of contaminated material will, potentially, continue to increase until either a maximum value, or equilibrium, is attained. The degree of equilibrium that is attained is dictated by the lifespan of the organism, and the length of exposure, in conjunction with the effective loss-rate constant. For the purposes of radiological protection we need to know the maximum potential body burden in the organism. If exposure is constant throughout the life of the organism, then the time of maximum body burden will definitely occur when the exposure time equals maximum lifespan of the organism (for radionuclides with a short half-life or biological elimination rate, the time to reach maximum body burden will be substantially shorter). Using the lifespan of the organism to calculate tissue concentrations is the simplest approach.

In a manner similar to metabolic rate and inhalation rate, the maximum lifespan of an organism has been found to scale as a function of body mass. Calder (1984) analyzed the lifespan of 35 species of wild mammals to estimate their life expectancy (in the wild):

$$T_{expected,wild} = 1.02\ M^{0.30 \pm 0.026}$$

Equation 20

where $T_{expected,wild}$ is in years and M is the live weight in kg.

3.4.1.4 Calculating Species-Independent Tissue Concentrations from Soil Exposure

The activity in an organism continuously exposed to a constant source of contaminated material will, potentially, continue to increase until either a maximum value, or equilibrium, is attained. The degree of equilibrium that is attained is dictated by the lifespan of the organism, and the length of exposure, in conjunction with the effective loss-rate constant. If exposure is constant throughout the life of the organism, then the time of maximum body burden will occur when the exposure time equals the maximum lifespan of the organism (for radionuclides with a short half-life or biological elmininination rate, the time to reach maximum body burden will be substantially shorter). Equations 11, 13, 18, and 20 can be combined (with appropriate unit conversions) to provide an estimate of the maximal tissue concentration for the organism consuming contaminated plants, soil, and breathing contaminated air:

$$C_{animal\ soil} = \frac{f_1 C_{soil} \left[(B_{iv} + f)\left(10^{-3} \frac{a}{dc} 70M^{0.75} \right) + \frac{PT}{IT} X\ 0.481M^{0.76} \right] \left(1 - e^{-(k_{rad} + k_{bio})(365.25)(1.02M^{0.3})} \right)}{(k_{rad} + k_{bio})M}$$

Equation 21

3.4.1.5 Calculating Limiting Soil Concentrations (BCGs) Using the Kinetic/Allometric Method: An Example

Although predicting tissue concentrations of species exposed to contaminants is important, the overall purpose of this effort is to derive media concentrations that will be protective of biota at a site. The methodology can be demonstrated using the soil-terrestrial animal pathway. Equation 21 estimates the maximum potential tissue concentration in an animal from prolonged exposure to soil contaminated with radionuclide *i* at a unit concentration (e.g., 1 Bq/kg). If a particular dose limit is chosen (D_{ta} for example, in Gy/y), the limiting soil concentration to achieve that dose limit (LS_i) can be calculated as:

$$LS_i = \frac{D_{ta}}{C_{animal,i} DCF_{internal,i}}$$

Equation 22

where LS_i = limiting soil concentration in Bq/kg;

D_{ta} = chosen dose limit, in Gy/y;

C_{animal} = predicted tissue concentration of an animal from exposure to 1 Bq/kg contamination in soil; and

DCF = internal dose factor (Gy/y per Bq/kg of tissue).

The equation can be further modified to account for external exposure of the organism:

$$LS_i = \frac{D_{ta}}{C_{animal,i} DCF_{internal,i} + DCF_{ext,i}}$$

Equation 23

where $DCF_{ext,i}$ = external dose conversion factor (Gy/y per Bq/kg of soil); and all other factors have been defined.

Substitution of the tissue concentrations (Equation 21) into the equation for calculating limiting media concentrations results in the following equation:

$$LS_{terrestrial\ animal,i} = \frac{0.001 Gy \cdot d^{-1}}{\dfrac{f_1(\alpha + \beta)\delta DCF_{internal,i}}{K_{eff} M} + DCF_{ext,soil,i}}$$

Equation 24

where α provides an estimate of the daily intake rate of contaminated food and soil into the terrestrial animal;

$$\alpha = \frac{a}{dc} 70M^{0.75}(B_{iv,sp,i} + f)$$

Equation 25

β provides the estimate of the daily intake that occurs through inhalation (and adjusts uptake relative to ingestion);

$$\beta = \frac{PT}{IT} X \; 0.481M^{0.76}$$

Equation 26

and δ provides an estimate of the exposure period, expressed as a function of the maximal life span of the target organism;

$$\delta = \left(1 - e^{-k_{eff} 1.02M^{0.30}}\right)$$

Equation 27

and all other terms have been previously defined.

3.4.2 Application of the Kinetic/Allometric Method in the Derivation of BCGs for Riparian Animals

In the analysis phase of the graded approach, a user may not have access to site-specific B_{iv}s or lumped parameters, or use of them results in exceeding site-specific screening. If that is the case, the user is allowed to conduct a more in-depth analysis of potential dose using the kinetic/allometric method. Equations have been developed for riparian animals using the methodology and equations discussed in Section 3.4.1. Two equations were developed, one for exposure to contaminated sediment, and a second for exposure to contaminated water.

Sediment. Riparian animal exposure to sediment considers external exposure as well as the inadvertent ingestion of sediment. The derivation of the sediment BCG for riparian animals is based on predicting maximal tissue concentrations after a lifetime of exposure**.** The equation used to derive the riparian BCGs for exposure to a single nuclide in contaminated sediment is:

$$BCG(sediment)_{i,riparian\ animal} = \frac{365.25 \times DL_{ra}}{CF_{ra} \times \left(\left[\frac{f_1 f \left[10^{-3} \frac{a}{dc} 70M^{0.75} \right] \left(1 - e^{-(k_{rad}+k_{bio})(365.25) \times 1.02M^{0.3}} \right) DCF_{internal,i}}{\left(k_{rad}+k_{bio} \right) M} \right] + \left[DCF_{ext,sediment,i} \right] \right)}$$

Equation 28

Water. The equation used to derive the riparian BCGs for exposure to a single nuclide in contaminated water is similar but includes ingestion of contaminated foodstuff and water, as well as external exposure, and is based on predicting maximal tissue concentrations after a lifetime of exposure. Water consumption scales as a function of body mass (EPA 1993) in a manner similar to ingestion:

Equation 29

$$r_{water} = 0.099M^{0.90}$$

where r_{water} is in Ld^{-1} and all other terms have been defined.

The BCG is calculated as:

$$BCG(water)_{i,riparian\ animal} = \frac{365.25 \times DL_{ra}}{CF_{ra} \left[\left(0.001 \times \frac{f_1 \left[B_{iv,af} \left(10^{-3} \frac{a}{dc} 70M^{0.75} \right) + 0.099M^{0.90} \right] \left(1 - e^{-(k_{rad}+k_{bio})(365.25) \times 1.02M^{0.3}} \right) (DCF_{internal,i})}{(k_{rad}+k_{bio})M} \right) + (DCF_{ext,water,i}) \right]}$$

Equation 30

where $B_{iv,af}$ = aquatic foods bioconcentration factor and all other terms have been defined.

It should be noted that Equations 28 and 30 can be condensed to the simpler form of Equations 3 and 4 by substitution of a single lumped parameter constant for the organism-specific variables. Also, it is possible to use Equation 30 to assess impacts to either carnivorous or herbivorous riparian animals by substituting appropriate values of $B_{iv,aa}$ into this equation. This method is applicable to carnivores because the lumped parameters selected for the default case represent the upper-end values from the technical literature. These literature values encompass carnivores as well as herbivores. The bioconcentration factor ($B_{iv,aa}$) in Equation 30, when multiplied by the water concentration, provides a prediction of radionuclide concentration in the riparian animal's food. For herbivorous riparian animals, one can substitute B_{iv} values appropriate for aquatic plant:water in lieu of $B_{iv,aa}$ values for aquatic animals.

3.4.3 Application of the Kinetic/Allometric Method in the Derivation of BCGs for Terrestrial Animals

In a manner similar to that used for riparian animals, equations have been developed for terrestrial animals using the methodology and equations discussed in section 3.4.1.

Soil. The derivation of the soil BCG considers ingestion of contaminated foodstuff, and soil, inhalation of soil, and external exposure. It is based on predicting maximal tissue concentrations after a lifetime of exposure.

$$BCG(soil)_{i,\text{terrestrial animal}} = \frac{365.25 \times DL_{ta}}{CF_{ta}\left[\dfrac{f_1\left[(B_{iv}+f)\left(10^{-3}\dfrac{a}{dc}70M^{0.75}\right)+\dfrac{PT}{IT}X\ 0.481M^{0.76}\right]\left(1-e^{-(k_{rad}+k_{bio})(365.25)(1.02^{0.3})}\right)(DCF_{internal,i})}{(k_{rad}+k_{bio})M}+(DCF_{ext,soil,i})\right]}$$

Equation 31

where all terms have been defined.

Water. The equation used to derive the terrestrial animal BCGs for exposure to a single nuclide in contaminated water is similar to that used for soil, but includes ingestion of contaminated water, as well as external exposure, and is based on predicting maximal tissue concentrations after a lifetime of exposure.

$$BCG(water)_{i,\text{terrestrial animal}} = \frac{365.35 \times DL_{ra}}{CF_{ta}\left[0.001\dfrac{f_1 0.099M^{0.90}\left(1-e^{-(k_{rad}+k_{bio})(365.25)(1.02M^{0.3})}\right)(DCF_{internal,i})}{(k_{rad}+k_{bio})M}+(DCF_{ext,i})\right]}$$

Equation 32

where all terms have been defined.

It should be noted that Equations 31 and 32 could be condensed to the simpler form of Equations 9 and 10 by substitution of a single lumped parameter constant for the organism-specific variables. Also, it is possible to use Equation 31 to assess impacts to either carnivorous or herbivorous animals by substituting appropriate values of B_{iv} into this equation. The bioconcentration factor ($B_{iv,tp}$) in Equation 31, when multiplied by the soil concentration, provides a prediction of radionuclide concentration in the terrestrial animal's food. While B_{iv} values for animal:soil could be substituted, a more conservative approach is to use the existing ($B_{iv,tp}$) values provided for terrestrial plants. In this manner, biomagnification through higher trophic levels can be assessed.

3.5 Selection of Lumped Parameters for Riparian and Terrestrial Animals

Recall that the general screening phase of the graded approach utilizes lumped parameters to provide estimates of organism tissue concentration, and ultimately derive the nuclide, media, and organism–specific BCGs. While there is a relative abundance of data for aquatic animals and terrestrial plants, less information is found for terrestrial and riparian animals.

As noted in Sections 3.4.2 and 3.4.3, the kinetic/allometric equations can be condensed to a simpler form by substitution of a single lumped parameter in place of the organism-specific variables. The choice of a value for this lumped parameter becomes problematic, however, when considering the range of organism types meant to be covered by the method. Also, there is very limited data available in the literature on animal:water, animal:soil, and animal:sediment ratios. Two alternative approaches were evaluated:

Calculating Lumped Parameters by Multiplying Related Concentration Ratios (Product Approach). It is possible to calculate the lumped parameters by multiplying related concentration ratios; for example, the product of plant:soil and animal:plant concentration ratios yields a animal:soil ratio which may be substituted for the lumped parameter used in Equation 9. This approach must be used with caution, as the data used in the process are most likely from different sources. This approach also is hampered by the lack of environmental data.

Calculating Lumped Parameters by Using Uncertainty Analysis on the Kinetic/Allometric Method. An alternative method to developing lumped parameters for riparian and terrestrial animals was addressed by using uncertainty analysis on the kinetic/allometric method. A Monte-Carlo simulation was used to determine the effect of parameter variability on the calculation of maximal animal tissue concentrations relative to environmental media concentrations. The allometric equations shown for riparian and terrestrial animals in Section 3.4.2 and 3.4.3, respectively, were rearranged to predict lumped parameters resulting from exposure to a unit concentration of contaminant in water, sediment, or soil. The rearranged equations are shown below. Each of the variables has been previously defined.

$$LP(\mathrm{sediment})_{i,\mathrm{riparian\ animal}} = \frac{C_{\mathrm{riparian\ animal\ sediment}}}{C_{\mathrm{sediment}}} = \frac{f_1 f \left[10^{-3}\frac{a}{dc}70M^{0.75}\right]\left(1 - e^{-(k_{rad}+k_{bio})(365.25)\,(1.02M^{0.3})}\right)}{(k_{rad}+k_{bio})M}$$

Equation 33

$$LP(water)_{i,\text{riparian animal}} = \frac{C_{i,\text{riparian animal}}}{C_{water}} = \frac{f_1\left[B_{iv\ af}\left(10^{-3}\frac{a}{dc}70M^{0.75}\right)+0.099M^{0.9}\right]\left(1-e^{-(k_{rad}+k_{bio})(365.25)(1.02M^{0.3})}\right)}{(k_{rad}+k_{bio})M}$$

Equation 34

$$LP(soil)_{i,\text{terrestrial animal}} = \frac{C_{\text{animal soil}}}{C_{soil}} = \frac{f_1\left[(B_{iv}+f)\left(10^{-3}\frac{a}{dc}70M^{0.75}\right)+\frac{PT}{IT}X\ 0.481M^{0.76}\right]\left(1-e^{-(k_{rad}+k_{bio})(365.25)(1.02M^{0.3})}\right)}{(k_{rad}+k_{bio})M}$$

Equation 35

$$LP(water)_{i,\text{riparian animal}} = \frac{C_{\text{animal, water}}}{C_{water}} = \frac{f_1\ 0.099M^{0.90}\left(1-e^{-(k_{rad}+k_{bio})(365.25)(1.02M^{0.3})}\right)}{(k_{rad}+k_{bio})M}$$

Equation 36

A Monte Carlo uncertainty analysis was conducted on each equation, with parameters varied over their known ranges. The range of values assigned each variable used in the uncertainty analysis was taken from the technical literature. These values, and their accompanying distributions, are shown in Table 3.1.

Ten thousand simulations were run for each equation and nuclide. Results were generated for twenty-three radionuclides, and the 95th percentile value for each was compared with data (where it existed) from the technical literature. The results are tabulated in Table 3.2 (A-D). Based on analysis, the model predictions tracked reasonably well with the values observed in the scientific literature. The lumped parameter value selected (from a choice of available empirical data, product approach, and uncertainty analysis on the kinetic/allometric method) for use as the default lumped parameter for use in general screening is highlighted in each table. The preference was to use empirical data where available and of good quality, as was the case for many terrestrial animal:soil values. However, as previously discussed, data for riparian and terrestrial animals was generally limited. In most instances, the kinetic/allometric result was chosen over values taken from the technical literature. Generally, the kinetic/allometric calculation resulted in a higher estimate of the lumped parameter. This is expected, owing to the generally conservative nature of parameter values used in the kinetic/allometric method.

Table 3.1 Parameters Used in Kinetic/Allometric Method Uncertainty Analysis for Riparian and Terrestrial Animals

Equation and Parameter	Mean	Range (and distribution)[a]
Riparian animal: sediment and water lumped parameter assessment		
$r_{ra} = \frac{a}{dc} 70 M^{b}$	r_{ra} = food intake rate in g/day	
$r_{ra,sediment} = \frac{a}{dc} 70 M^{b} f$	$r_{ra,sediment}$ = sediment intake rate in g/day;	
a, ratio of active to maintenance metabolic rate (see equation 13)	2	0.5-3.0 (normal)
d, fraction of energy ingested that is assimilated (see equation 13)	0.65	0.3-0.9 (normal)
c, caloric value of food intake (see equation 13)	5	4 – 9 (normal)
b, exponent in allometric relationship detailing consumption as a function of body mass (see equation 13)	0.75	0.68-0.8 (normal)
f, fraction of diet that is soil (see equation 15)	0.1	0.01-0.55 (normal)
M, body mass in kilograms	1 kg	0.02 – 6000 (log normal)
$T_{ls} = 1.02\ M^{0.30}$	T_{ls} = maximum lifespan of the organism, years	
exponent (0.30), allometric relationship detailing lifespan as a function of body mass (see equation 20)	0.3	0.25 – 0.33 (normal)
constant (1.02), allometric relationship, detailing lifespan as a function of body mass (equation 20)	1.02	0.9 – 2.00 (normal)
$\lambda_{bio,i} = \frac{0.69315}{a M^{b}}$	$\lambda_{bio,i}$= biological decay constant of material in organism**,** per day	
b, exponent, allometric relationship detailing biological half-time as a function of body mass (equation 19)	Varies by nuclide 0.24 for Cs	0.15 – 0.3 (normal)
a, constant, allometric relationship, detailing biological half-time as a function of body mass (equation 19)	Varies by nuclide 3.5 for Cs	2 - 5 (normal)
$I_{w} = 0.099\ M^{0.9}$	I_{w} =water intake, L/d	
constant, allometric relationship, detailing water intake rate I_w(l/d) as a function of body mass, where $I_w = 0.099W^{0.90}$	0.099	0.07 - 0.13 (normal)
exponent, allometric relationship, detailing water intake rate as a function of body mass where $I_w = 0.099W^{0.90}$	0.9	0.63 - 1.17 (normal)

Table 3.1 (Continued) Parameters Used in Kinetic/Allometric Method Uncertainty Analysis for Riparian and Terrestrial Animals

Equation and Parameter	Mean	Range (and distribution)[a]
Terrestrial animal: soil and water lumped parameter assessment		
$r_{inhale,i}$ ' 0.481 $M^{0.76}$	$r_{iinhale,\ i}$ = inhalation rate of soil	
exponent (0.76), allometric relationship detailing inhalation rate as a function of body mass (equation 16)	0.76	0.64-0.86 (normal)
X Dust loading (equation 16)	0.001	0.0001 – 0.01 (log normal)
constant (0.481), allometric relationship, detailing inhalation rate as a function of body mass (equation 16)	0.481	0.001 – 0.66 (normal)
$r_{ta,soil} = r_{ra,sed}$ $r_{ta} = r_{ra}$ all other factors have been defined.	Varies	Varies
[a]The distributions used in this assessment were created by examination of the range of values of the input variables and, where possible, by testing using the forecasting and risk analysis software, Crystal Ball®.		

Table 3.2A A Comparison of Lumped Parameter Values Determined by Uncertainty Analysis on the Kinetic/Allometric Method, Product Approach, and Empirical Data (Literature Values): Riparian Animal to Sediment[a]

Element	Calculated as Product of Concentration Ratios (CR)	Animal to Sediment Value Kinetic/Allometric Method		Empirically Measured Lumped Parameter
		50th percentile	95th percentile	
Am	5.4E-05	3.6E-04	3.1E-03	1.4E-04
Ce	3.9E-02	1.5E-04	4.8E-04	
Cs	4.4E-01	1.2E-01	2.7E-01	
Co	4.0E-02	4.3E-03	1.0E-02	4.5E-01
Eu		5.9E-04	3.9E-03	
H	6.0E-01	1.2E-01	4.3E-01	
I	1.1E+00	1.3E-01	3.2E-01	
Pu	3.0E-06	3.6E-04	3.2E-03	5.0E-05
Ra	3.0E-02	1.4E-02	3.0E-02	
Sb	1.8E-03	1.8E-04	4.1E-04	
Sr	3.6E-01	1.1E+00	2.0E+00	
Tc	1.2E-02	1.7E-02	4.6E-02	
Th	2.4E-07	2.9E-04	1.9E-03	
U	1.0E-01	1.6E-03	3.8E-03	1.0E-03
Zn		7.2E-01	1.8E+00	
Zr	6.4E-03	1.1E-03	3.0E-03	

[a]The shaded cell indicates this value is used as the default lumped parameter in the general screening phase of the graded approach. Blank cells indicate data was unavailable.

Table 3.2B A Comparison of Lumped Parameter Values Determined by Uncertainty Analysis on the Kinetic/Allometric Method, Product Approach, and Empirical Data (Literature Values): Riparian Animal to Water[a]

Element	Calculated as Product of Concentration Ratios (CR)	Animal to Water Value Kinetic/Allometric Method		Empirically Measured Lumped Parameter
		50th Percentile	95th Percentile	
Am	2.2E-02	1.4E+00	1.2E+01	
Ce	3.9E+01	1.4E+01	3.5E+01	
Cs	1.5E+05	2.6E+04	4.7E+04	2.5E+05
Co	1.0E+03	8.6E+01	1.6E+02	9.0E+02[b]
Eu		3.6E+00	2.0E+01	
H	1.2E-01	2.4E-01	8.1E-01	
I	1.1E+02	2.9E+02	5.7E+02	2.1E+02
Pu	1.5E-02	3.6E+00	3.0E+01	6.7E+00
Ra	3.2E+01	4.6E+02	8.0E+02	
Sb	1.8E+00	1.7E-01	3.1E-01	
Sr	1.4E+03	3.5E+03	6.2E+03	9.0E+03[b]
Tc	1.0E+01	1.4E+01	2.9E+01	
Th	2.4E-01	2.4E-01	1.5E+00	
U	5.1E+00	1.6E+01	3.0E+01	
Zn		1.2E+05	2.5E+05	
Zr	5.0E+02	1.8E+01	4.0E+01	

[a] The shaded cell indicates this value is used as the default lumped parameter in the general screening phase of the graded approach. Blank cells indicate data was unavailable.

[b] These values are not directly measured lumped parameters but were derived from other parameters.

Table 3.2C A Comparison of Lumped Parameter Values Determined by Uncertainty Analysis on the Kinetic/Allometric Method, Product Approach, and Empirical Data (Literature Values): Terrestrial Animal to Soil[a]

Element	Calculated as Product of Concentration Ratios (CR)	Animal to Soil Value Kinetic/Allometric Method		Empirically Measured Lumped Parameter
		50th Percentile	95th Percentile	
Am	4.1E-07	3.7E-04	4.0E-03	1.0E-04
Ce	1.7E-04	2.0E-04	5.5E-04	5.5E-03
Cs	6.7E+01	1.1E+01	2.0E+01	1.0E+02
Co	1.1E-01	1.0E-02	3.0E-02	8.0E-02
Eu		7.9E-04	4.6E-03	
H	6.6E-01	1.3E+00	4.3E+00[b]	
I	2.0E-01	6.8E-01	1.4E+00	3.0E+00
Pu	2.2E-07	4.1E-04	3.0E-03	3.0E-03
Ra	1.1E-03	3.0E-02	6.0E-02	2.1E-01
Sb	1.8E-04	1.9E-04	4.3E-04	
Sr	1.7E+01	4.2E+01	7.6E+01	6.1E-01
Tc	1.0E+00	1.4E+00	3.1E+00	
Th	3.1E-06	2.9E-04	1.6E-03	1.0E-03
U	1.9E-05	1.7E-03	4.1E-03	1.0E-03
Zn		3.3E+00	7.0E+00	1.0E-02
Zr	9.1E-03	1.4E-03	3.5E-03	

[a]The shaded cell indicates this value is used as the default lumped parameter in the general screening phase of the graded approach. Blank cells indicate data was unavailable.
[b] The H lumped parameter value was set at a default of 1.0 for calculation of the generic BCG.

Table 3.2D A Comparison of Lumped Parameter Values Determined by Uncertainty Analysis on the Kinetic/Allometric Method, Product Approach, and Empirical Data (Literature Values): Terrestrial Animal to Water[a]

Element	Calculated as Product of Concentration Ratios (CR)	Animal to Water Value Kinetic/Allometric Method		Empirically Measured Lumped Parameter
		50th Percentile	95th Percentile	
Am		5.6E-03	8.6E-02	
Ce		2.4E-03	8.2E-03	
Cs	1.1E+01	2.0E+00	3.4E+00	
Co	7.9E-01	7.5E-02	1.3E-01	
Eu		9.2E-03	9.7E-02	
H		1.9E+00	1.7E+01[b]	
I		2.2E+00	3.4E+00	5.4E+00
Pu	1.5E-05	5.6E-03	9.3E-02	
Ra	1.8E+01	2.4E-01	4.0E-01	
Sb		3.0E-03	5.2E-03	
Sr	6.4E+02	1.8E+01	3.1E+01	
Tc		2.7E-01	8.4E-01	
Th		4.6E-03	4.5E-02	
U	1.9E-04	3.0E-02	5.0E-02	1.0E-03
Zn		3.7E+00	2.0E+01	1.0E-02
Zr	9.1E-03	1.8E-02	3.1E-02	

[a]The shaded cell indicates this value is used as the default lumped parameter in the general screening phase of the graded approach. Blank cells indicate data was unavailable.

[b] The H lumped parameter value was set at a default of 1.0 for calculation of the generic BCG.

4 Default Parameters and Their Sources

The following sections describe the source of parameter values used in the derivation of BCGs for aquatic animals, riparian animals, terrestrial plants, and terrestrial animals.

4.1 Bioaccumulation Factors (B_{iv}s)

The $B_{iv,aa,i}$ values for aquatic animals were selected from across all sampled aquatic taxa and include predatory fin fish, crustaceans, and other organisms. Typically the most limiting values come from crustaceans or molluscs. The specific source of default values used for the general screening phase of the graded approach for aquatic animal evaluations is shown in Table 4.1. Table 4.2 provides the values used for the general screening phase in the derivation of terrestrial plant BCGs.

Table 4.1 Default Bioaccumulation Factors (B_{iv}s) for Aquatic Animals

Radionuclide	$B_{iv,aa,i}$ Organism to Water (L/kg) fresh mass	Water $B_{iv,aa,i}$ Reference	Comment
^{241}Am	400	CRITR	Value for fresh water molluscs taken from CRITbiog.dat (generic bioaccumulation: 2000) and converted to wet weight basis by dividing by 5 (an arbitrary dry to wet weight conversion). Conversation with D Strenge and B Napier indicated the GENII and CRITR values are dry-weight basis.
^{144}Ce	9000	T&M T. 5.41	Maximum fresh weight value for molluscs.
^{135}Cs	22000	T&M T. 5.41	Maximum value for crustaceans, fresh weight, for ^{133}Cs, ^{134}Cs, ^{137}Cs.
^{137}Cs	22000	T&M T. 5.41	Maximum value for crustaceans, fresh weight, for ^{133}Cs, ^{134}Cs, ^{137}Cs.
^{60}Co	2000	T&M T. 5.41	Maximum fresh weight value for molluscs.
^{154}Eu	600	GENII	Value for fresh water molluscs taken from BIOAC1.dat (generic bioaccumulation: 3000) and converted to wet weight basis by dividing by 5 (an arbitrary dry to wet weight conversion). Conversation with D Strenge and B Napier indicated the GENII and CRITR values are dry-weight basis.
^{155}Eu	600	GENII	Value for fresh water molluscs taken from BIOAC1.dat (generic bioaccumulation: 3000) and converted to wet weight basis by dividing by 5 (an arbitrary dry to wet weight conversion). Conversation with D Strenge and B Napier indicated the GENII and CRITR values are dry-weight basis.
^{3}H	0.2	CRITR	Value for fresh water molluscs taken from CRITbiog.dat (generic bioaccumulation: 1) and converted to wet weight basis by dividing by 5 (an arbitrary dry to wet weight conversion). Conversation with D Strenge and B Napier indicated the GENII and CRITR values are dry-weight basis.
^{129}I	220	T&M T. 5.41	Maximum fresh weight value for molluscs.
^{131}I	220	T&M T. 5.41	Maximum fresh weight value for molluscs.
^{239}Pu	1000	T&M T. 5.41	Maximum fresh weight value for crustaceans.
^{226}Ra	3200	T&M T. 5.41	Freshwater gammarus.
^{228}Ra	3200	Ra-226	Freshwater gammarus.
^{125}Sb	100	T&M T. 5.41	Maximum fresh weight value for fish.
^{90}Sr	320	T&M T. 5.41	Maximum fresh weight value for molluscs.
^{99}Tc	78	T&M T. 5.41	Maximum fresh weight value for fish.
^{232}Th	80	T&M T. 5.41	Maximum fresh weight value for fish.
^{233}U	1000	T&M T. 5.41	Maximum fresh weight value for molluscs.
^{234}U	1000	T&M T. 5.41	Maximum fresh weight value for molluscs.
^{235}U	1000	T&M T. 5.41	Maximum fresh weight value for molluscs.
^{238}U	1000	T&M T. 5.41	Maximum fresh weight value for molluscs.
^{65}Zn	17000	T&M T. 5.41	Maximum fresh weight values for snails.
^{95}Zr	1600	T&M T. 5.41	Maximum fresh weight values for snails.

Table 4.2 Default Bioaccumulation Factors (B_{iv}s) for Terrestrial Plants

Radionuclide	$B_{iv,tp,i}$, Plant to Soil Bq/kg wet weight to Bq/kg soil (dry) mass	Plant $B_{iv,tp,i}$ Reference, Bq/kg plant (wet weight) per Bq/kg soil	Comment
^{241}Am	8.0E-03	T&M T5.16, T 5.18	Calculated from a CR value of 0.042 (dry wt/dry wt) for grasses. Converted to Biv using wet/dry ratio of 5.5. Note this also includes aerial deposition.
^{144}Ce	4.0E-02	T&M T5.16, T 5.17	Converted from a CR value (0.22 -dry wt/dry wt) for grasses in a soil with low pH content (<5.5). Converted to Biv using wet/dry ratio of 5.5
^{135}Cs	1.0E+01	T&M T5.16, T 5.17	Calculated from a CR value (42.6 - dry wt/dry wt) for legumes in Florida soils with low K content. Converted to Biv using wet/dry ratio of 4.5
^{137}Cs	1.0E+01	T&M, T5.16, T 5.17	Calculated from a CR value (42.6 - dry wt/dry wt) for legumes in Florida soils with low K content. Converted to Biv using wet/dry ratio of 4.5
^{60}Co	2.0E-01	T&M T5.16, T 5.17	Calculated from a CR value of 1 (dry wt/dry wt) for grasses in histosol soils. Converted to Biv using wet/dry ratio of 4.5
^{154}Eu	4.0E-02	Estimated from Ce value by KAH	
^{155}Eu	4.0E-02	Estimated from Ce value by KAH	
^{3}H	1.0E+00	NUREG 1.109	NUREG 1.109 and divided by a wet to dry conversion value of 4.5
^{129}I	4.0E-01	T&M T5.16, T 5.17	Calculated from a CR value of 1.84 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. Note this also includes aerial deposition.
^{131}I	4.0E-01	T&M T5.16, T 5.17	Calculated from a CR value of 1.84 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. Note this also includes aerial deposition.
^{239}Pu	1.0E-02	T&M T5.16, T 5.18	Calculated from a CR value of 0.066 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. Note this also includes aerial deposition.
^{226}Ra	1.0E-01	T&M T5.16, T 5.18	Calculated from a CR value of 0.49 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. Note this also includes aerial deposition.

Table 4.2 (Continued) Default Bioaccumulation Factors (B_{iv}s) for Terrestrial Plants

Radionuclide	$B_{iv,tp,i}$, Plant to Soil Bq/kg wet weight to Bq/kg soil (dry) mass	Plant $B_{iv,tp,i}$ Reference, Bq/kg plant (wet weight) per Bq/kg soil	Comment
^{228}Ra	1.0E-01	T&M, T5.16, T 5.18	Calculated from a CR value of 0.49 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. Note this also includes aerial deposition.
^{125}Sb	1.0E-02	GENII	Taken from GENII and converted to wet weight basis by dividing by 5 (an arbitrary wet to dry weight conversion). Conversation with D Strenge and B Napier indicated the GENII and CRITR ftrans values are on a dry-weight basis.
^{90}Sr	4.0E+00	T&M T5.16, T 5.17	Converted from a CR value (17.3 -dry wt/dry wt) for legumes in a soil with low Ca content. Converted to Biv using wet/dry ratio of 4.5
^{99}Tc	8.0E+00	GENII	Taken from GENII and converted to wet weight basis by dividing by 5 (an arbitrary wet to dry weight conversion). Conversation with D Strenge and B Napier indicated the GENII and CRITR ftrans values are on a dry-weight basis.
^{232}Th	1.0E-03	T&M T5.16, T 5.18	Calculated from a CR value of 0.0046 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. Note this also includes aerial deposition.
^{233}U	4.0E-03	T&M T5.16 T 5.18	Calculated from a CR value of 0.017 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. Note this also includes aerial deposition.
^{234}U	4.0E-03	Ti&M T5.16, T 5.18	Calculated from a CR value of 0.017 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. Note this also includes aerial deposition.
^{235}U	4.0E-03	T&M T5.16, T 5.18	Calculated from a CR value of 0.017 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. Note this also includes aerial deposition.
^{238}U	4.0E-03	T&M T5.16, T 5.18	Calculated from a CR value of 0.017 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. Note this also includes aerial deposition.
^{65}Zn	3.0E-01	T&M T5.16, T 5.17	Calculated from a CR value of 1.5 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5. This value includes external (aerial) deposition in the value.
^{95}Zr	3.0E-02	T&M T5.16, T 5.17	Calculated from a CR value of 0.13 (dry wt/dry wt) for legumes. Converted to Biv using wet/dry ratio of 4.5.

4.2 Distribution Coefficients

Distribution coefficients describe the partitioning of a radionuclide between water and soil or sediment. Denoted by the variable K_d, these parameters were used in the absence of water (or sediment) data to estimate the missing radionuclide concentration data. Specific instructions on the use of this parameter are provided in Module 3, Section 3.2.3.

Table 4.3 Most Probable K_d Values for Use in Calculating BCGs for Sediment or Water for an Aquatic System Evaluation in the Absence of Co-Located Water and Sediment Data

Radionuclide	$K_{d,mp}$ Most Probable Values L/kg (mL/g)	Reference
^{241}Am	5.0E+03	Table 3.2, Till & Meyer, Median value for fresh water systems.
^{144}Ce	1.0E+03	RESRAD, Table E.3 page 202, "Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0" ANL/EAD/LD-2
^{135}Cs	5.0E+02	“”
^{137}Cs	5.0E+02	“”
^{60}Co	1.0E+03	“”
^{154}Eu	5.0E+02	Table 3.2, Till & Meyer, Median value for fresh water systems.
^{155}Eu	5.0E+02	“”
^{3}H	1.0E-03	Estimated by Higley
^{129}I	1.0E+01	Table 3.2, Till & Meyer, Median value for fresh water systems.
^{131}I	1.0E+01	“”
^{239}Pu	2.0E+03	Value taken from RESRAD, Table E.3 page 202, "Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0" ANL/EAD/LD-2.
^{226}Ra	7.0E+01	“”
^{228}Ra	7.0E+01	“”
^{125}Sb	1.0E+00	“”
^{90}Sr	3.0E+01	Value taken from RESRAD, Table E.3 page 202, "Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0" ANL/EAD/LD-2.
^{99}Tc	5.0E+00	Table 3.2, Till & Meyer, Median value for fresh water systems.
^{232}Th	6.0E+04	Value taken from RESRAD, Table E.3 page 202, "Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0" ANL/EAD/LD-2.
^{233}U	5.0E+01	“”
^{234}U	5.0E+01	“”
^{235}U	5.0E+01	“”
^{238}U	5.0E+01	“”
^{65}Zn	2.0E+01	“”
^{95}Zr	1.0E+03	“”

4.3 Coefficients Used in the Kinetic/Allometric Method

The following tables list the values of kinetic/allometric coefficients used in the derivation of lumped parameters using the kinetic/allometric method.

Table 4.4 Source of Default f_1 Values Used for Riparian and Terrestrial Animals

Radionuclide	f_1, (unitless)	Comment
^{241}Am	1.0E-03	ICRP 30 part 4 values for human and animal studies.
^{144}Ce	3.0E-04	ICRP 30 part 1 values for human and animal studies.
^{135}Cs	1.0E+00	ICRP 30 part 1 values for human and animal studies.
^{137}Cs	1.0E+00	ICRP 30 part 1 values for human and animal studies.
^{60}Co	5.0E-02	ICRP 30 part 1 values for human and animal studies.
^{154}Eu	1.0E-03	ICRP 30 Part 3 values.
^{155}Eu	1.0E-03	ICRP 30 Part 3 values.
^{3}H	1.0E+00	ICRP 30 part 1 values for human and animal studies.
^{129}I	1.0E+00	ICRP 30 Part 1 values.
^{131}I	1.0E+00	ICRP 30 Part 1 values.
^{239}Pu	1.0E-03	ICRP 30 part 4 values for human and animal studies.
^{226}Ra	2.0E-01	ICRP 30 part 1 values for human and animal studies.
^{228}Ra	2.0E-01	ICRP 30 part 1 values for human and animal studies.
^{125}Sb	1.0E-02	ICRP 30 part 3 values for human and animal studies.
^{90}Sr	3.0E-01	ICRP 30 part 1 values for human and animal studies.
^{99}Tc	8.0E-01	ICRP 30 part 2 values for human and animal studies.
^{232}Th-	2.0E-04	ICRP 30 part 1 values for human and animal studies.
^{233}U	5.0E-02	ICRP 30 part 1 values for human and animal studies.
^{234}U	5.0E-02	ICRP 30 part 1 values for human and animal studies.
^{235}U	5.0E-02	ICRP 30 part 1 values for human and animal studies.
^{238}U	5.0E-02	ICRP 30 part 1 values for human and animal studies.
^{65}Zn	5.0E-01	ICRP 30 part 2 values for human and animal studies.
^{95}Zr	2.0E-03	ICRP 30 part 1 values for human and animal studies.

Table 4.5 Source of Data Used in Estimating Biological Half-Times for Riparian and Terrestrial Animals (see Equation 19, Section 3.4.1.2)

Radionuclide	α (constant)	β (exponent)	Reference
^{241}Am	0.8	0.81	ICRP 30 Part 4
^{144}Ce	1.4	0.8	ICRP 30 Part 1
^{135}Cs	3.5	0.24	Whicker & Schultz
^{137}Cs	3.5	0.24	Whicker & Schultz
^{60}Co	2.6	0.24	Whicker & Schultz
^{154}Eu	1.4	0.8	ICRP 30 Part 3
^{155}Eu	1.4	0.8	ICRP 30 Part 3
^{3}H	0.82	0.55	Whicker & Schultz
^{129}I	6.8	0.13	Whicker & Schultz
^{131}I	6.8	0.13	Whicker & Schultz
^{239}Pu	0.8	0.81	ICRP 30 Part 4
^{226}Ra	2	0.25	Estimated by KAH
^{228}Ra	2	0.25	Estimated by KAH
^{125}Sb	0.5	0.25	ICRP 30 Part 3
^{90}Sr	107	0.26	Whicker & Schultz
^{99}Tc	0.3	0.4	ICRP 30 Part 2
^{232}Th	3.3	0.81	ICRP 30 Part 1
^{233}U	0.8	0.28	ICRP 30 Part 1
^{234}U	0.8	0.28	ICRP 30 Part 1
^{235}U	0.8	0.28	ICRP 30 Part 1
^{238}U	0.8	0.28	ICRP 30 Part 1
^{65}Zn	100	0.25	ICRP 30 Part 2
^{95}Zr	100	0.25	ICRP 30 Part 1

Table 4.6 Factors Used in Assessing the Relative Contribution to Internal Dose from Animal Inhalation versus Ingestion

Radionuclide	PT/IT[a] (Correction Factor)
^{241}Am	250
^{144}Ce	16
^{135}Cs	0.8
^{137}Cs	0.8
^{60}Co	7
^{154}Eu	30
^{155}Eu	30
^{3}H	1
^{129}I	0.7
^{131}I	0.7
^{239}Pu	4000
^{226}Ra	3
^{228}Ra	3
^{125}Sb	3.5
^{90}Sr	200
^{99}Tc	5
^{232}Th	750
^{233}U	7000
^{234}U	7000
^{235}U	3500
^{238}U	4000
^{65}Zn	1
^{95}Zr	10

[a] Based on ICRP 30, parts 1-3 and Zach's (1985) analysis of the relative contribution of inhalation to an equivalent amount of soil ingestion dose for animals.

Table 4.7 Allometric Equations and Parameter Values Used in Estimating Intake of Riparian Animal Organisms

Parameter	Equation	Descriptions	Value(s)	Reference
W		Body mass (g)	8800	default for raccoon or river otter
r	$r = \frac{a}{dc} 70 M^{0.75}$	Food intake rate (g/d)	325.1377223	W&S, Vol. II, p. 43, equation 78
		a: ratio of active to basal metabolic rate	2	
		70: constant	70	
		d: fraction of energy ingested that is assimilated or oxidized	0.44	
		c: caloric value of food, kcal/g	5	
		M: body mass in kg	8.8	
		0.75: exponent in calculation	0.75	
$r_{sediment}$	$r_{sediment} = 0.1\ r$	Sediment Intake Rate (g/d)	32.51377223	EPA Wildlife Exposure Factor Handbook, Vol. 1, p. 4-22
		r: food intake rate, g/d	325.1377223	
		0.1: fraction of sediment in diet, expressed as % of food diet, dry	0.1	
T_{ls}	$T_{ls,\max} = 1.02 M^{0.30}$	Maximum Lifespan	1.958	Calder, p. 316, Table 11-5
		1.02: constant in equation	1.02	
		see above equation, M: body mass in kg	8.8	
		0.30: exponent in calculation	0.30	
r_b	$r_b = 0.481 M^{0.76}$	Inhalation rate (m^3/d)	2.511608286	Pedley, p. 15, Table V., adjusted to provide units of m^3/d
		0.481: constant in calculation to give m^3/d	0.481	
		see above equation, M: body mass in kg	8.8	
		0.76: exponent in equation	0.76	
$r_{inhalation}$	$r_{inhalation} = x r_b$	Sediment inhalation rate (g/d)	0.000251161	derived
		x: airborne dust loading, g/m^3	0.0001	
		r_b: inhalation rate (see above)	2.511608286	
I_w	$I_w = 0.099 M^{0.90}$	Water consumption rate (L/d)	0.700921852	EPA Wildlife Exposure Factor Handbook, Vol. 1, p. 3-10, equation 3-17
		0.099: constant in equation	0.099	
		see above equation, M: body mass in kg	8.8	
		0.9: exponent in calculation	0.9	

Table 4.8 Allometric Equations and Parameter Values used in Estimating Intake of Terrestrial Animal Organisms

Parameter	Equation	Descriptions	Value(s)	Reference
W		Body mass (g)	22	default for deer mouse
r	$r = \frac{a}{dc} 70 M^{0.75}$	Food intake rate (g/d)	3.635150245	W&S, Vol. II, p. 43, equation 78
		a: ratio of active to basal metabolic rate	2	
		70: constant	70	
		d: fraction of energy ingested that is assimilated or oxidized	0.44	
		c: caloric value of food, kcal/g	5	
		M: body mass in kg (=W*0.001)	0.022	
		0.75: exponent in calculation	0.75	
$r_{sediment}$	$r_{soil} = 0.1\ r$	Soil Intake Rate (g/d)	0.363515025	EPA Wildlife Exposure Factor Handbook, Vol. 1, p. 4-22
		r: food intake rate, g/d	3.635150245	
		0.1: fraction of sediment in diet, expressed as % of food diet, dry	0.1	
T_{ls}	$T_{ls,\max,} = 1.02 M^{0.3}$	Maximum Lifespan	.32	Calder, p. 316, Table 11-5
		1.02: constant in equation	1.02	
		see above equation, M: body mass in kg	0.022	
		0.30: exponent in calculation	0.30	
r_b	$r_b = 0.481 M^{0.76}$	Inhalation rate (m^3/d)	0.026447603	Pedley, p. 15, Table V., adjusted to provide units of m^3/d
		0.481: constant in calculation to give m^3/d	0.481	
		see above equation, M: body mass in kg	0.022	
		0.76: exponent in equation	0.76	
$r_{inhalation}$	$r_{inhalation} = x r_b$	Soil inhalation rate (g/d)	2.64476E-06	derived
		x: airborne dust loading, g/m^3	0.0001	
		r_b: inhalation rate (see above)	0.026447603	
I_w	$I_w = 0.099 M^{0.90}$	Water consumption rate (L/d)	0.003190183	EPA Wildlife Exposure Factor Handbook, Vol. 1, p. 3-10, equation 3-17
		0.099: constant in equation	0.099	
		see above equation, M: body mass in kg	0.022	
		0.9: exponent in calculation	0.9	

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Concluding Material

Review Activity:		**Preparing Activity:**
DOE Programs	Operations and Field Offices	DOE-EH-412
EH	AL	
EM	CH	**Project Number**:
SC	ID	
DP	NV	ENVR-0011
EE	OR	
FE	RL	
GC	SR	
IG	BPO	
NE	CAO	
NN	FETC-PA	
PO	FETC-WV	
RW	OH	
	OK	
	RF	

Laboratories

ANL	BNL
INEEL	EML
ORNL	FNAL
PNNL	LANL
SNL	LBNL
SREL	LLNL
AMES	NBL
ARG	SLAC
BHG	TJAF

Area Offices

Rocky Flats Area Office	Grand Junction Office
West Valley Area Office	Kirtland Area Office
Amarillo Area Office	Kansas City Area Office
Fernald Area Office	Miamisburg Area Office
Golden Field Office	Western Area Power Administration

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